College | Physical Sciences
Physics & Astronomy

A polarized positron sources based on high repetition rate FEL/IFEL cavity

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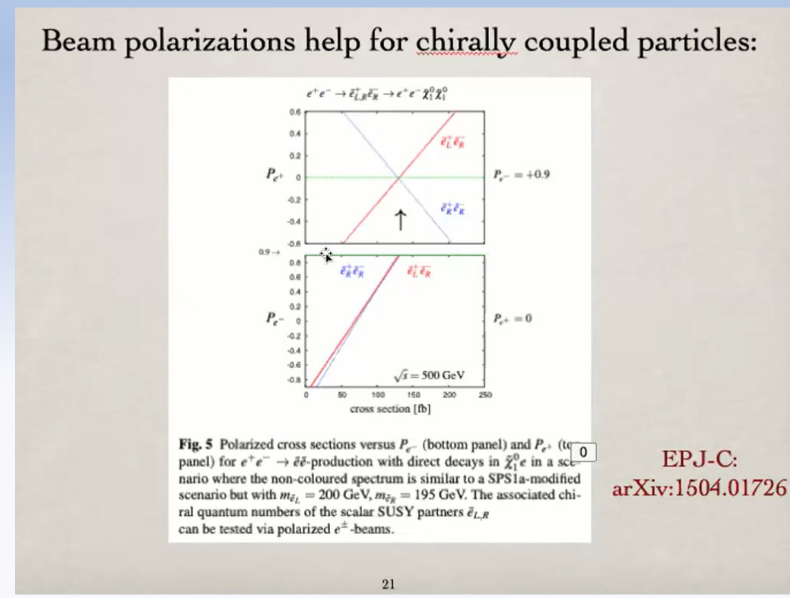
AAC workshop, Hauppage, Long Island, November 10th 2022

Outline

- Polarized positrons for High Energy Physics colliders
- Review of current plans for ILC positron source
- ICS-based alternative approach based on high efficiency FEL/IFEL optical cavity
- FAST-GREENS project

The need for polarized positrons in high energy physics

- Effective increase in luminosity with the correct helicity of both beams
- Decrease in background
- Uncover new BSM chiral physics

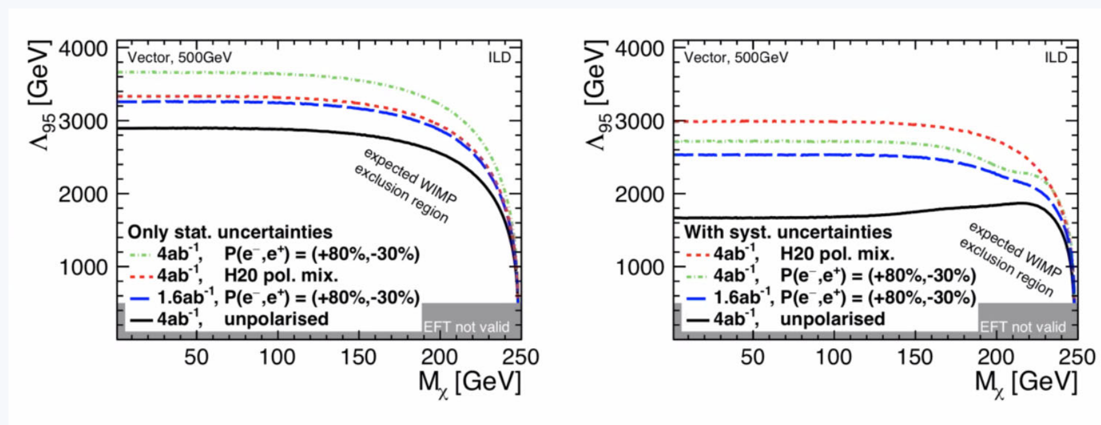


References:

T. Han - Snowmass Agora Dec 15th

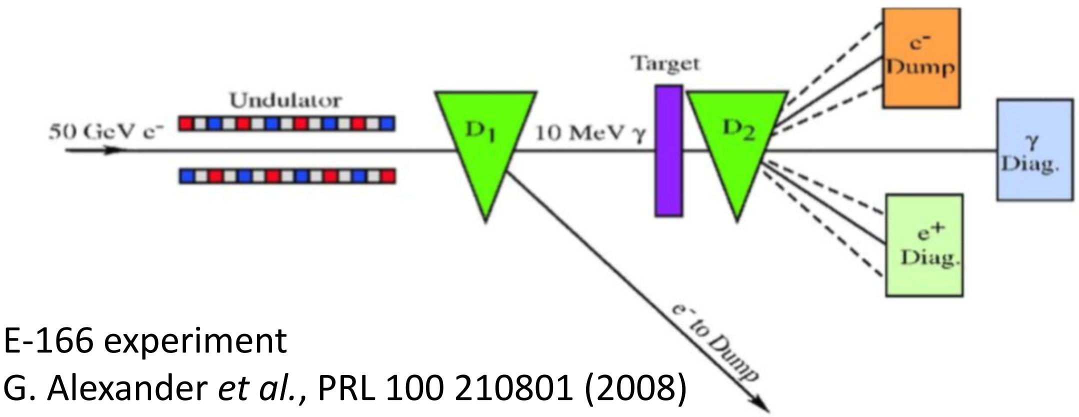
F. Dietrich et al. arXiv:1902.07744

ILC Snowmass report. Chapter 5



ILC polarized positron source

- Short period undulator to generate polarized gamma-rays using full energy e-beam
- Principle based on successful polarized positron generation at E-166
- Conversion in thin Ti-alloy target
- ILC extreme beam parameters spurred decade-long R&D on this topic
  - 230 m long 1.1 cm period undulator
  - 100 m/s 50 cm radius rotating wheel to distribute incident power
  - High field flux concentrator
  - 30 % polarized beams



E-166 experiment
G. Alexander *et al.*, PRL 100 210801 (2008)

ILC e+ beam parameters (nominal luminosity)

Number of positrons per bunch at IP	2×10^{10}
Number of bunches per pulse	1312
Repetition rate	5 Hz
Positrons per second at IP	1.3×10^{14}

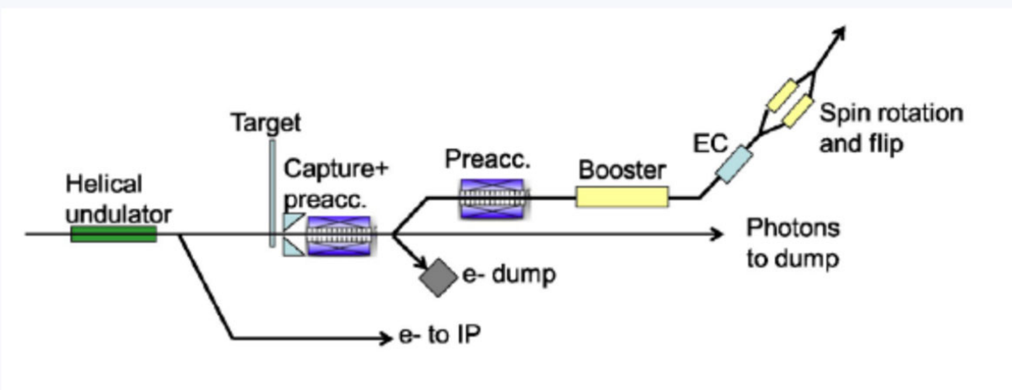
– Required positron yield: Y = 1.5e+/e- at damping ring

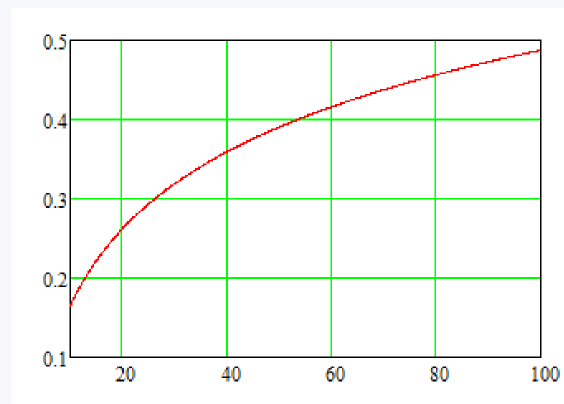
That's about a factor 100 more compared to SLC!

Note: Alternative conventional source in preparation based on 3 GeV e-beam on 3 X_0 W target
If source is independent, the format of positron bunch train has some freedom exploiting the damping ring to reshape the temporal structure (Omori et al.)

Some issues with current plans

- Very long, small gap superconducting undulator. Need to limit e-beam energy deposition.
- As CoM energy drops the undulator needs to get longer and the photon energy suffers (@125 GeV, 1.1 cm -> 7 MeV photons)
- Angular divergence is very small and this complicates the design of the target (1 mm spot size)
- Not-independent source: requires yield e+/e- to be larger than 1 since 125 GeV bunch is the main collider beam.





Photon energy (m_0c^2)

Polarized positrons in the Snowmass process

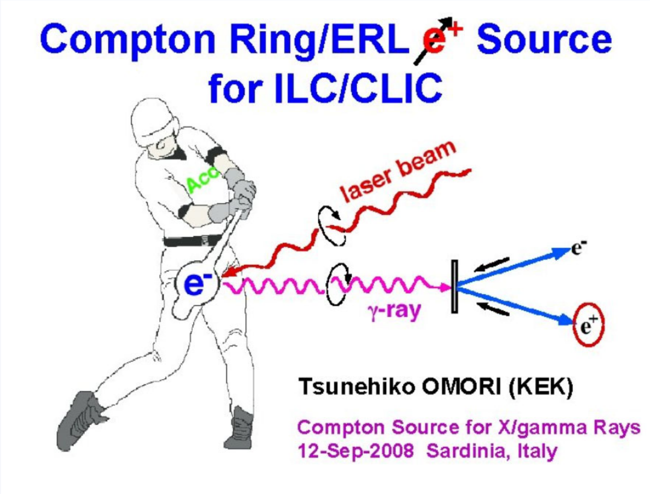
- Snowmass workshop https://indico.fnal.gov/event/52959/
- Snowmass white paper focusing on advanced accelerator technology for polarized positron sources https://arxiv.org/abs/2204.13245
- Laser-based undulator. Inverse Compton Scattering-based circularly polarized gamma-ray source for positron production

High photon energy (1 GeV + 515 nm) -> 34 MeV

Increase in yield and final polarization

Larger spot size at the target can be expanded to 5 mm as angular divergence is 125 times larger than undulator $\theta \sim 1/\gamma$

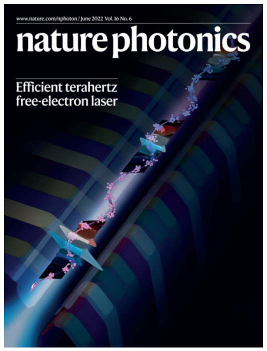
Number of initial e- is independent of number of positrons. Can be much larger than collision beam.



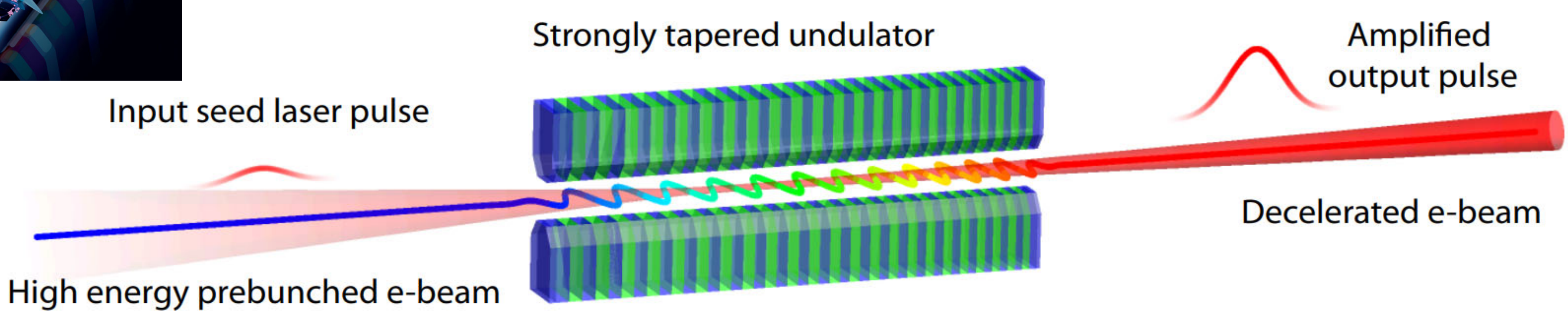
Smaller number of circularly polarized photons per electron from ICS interaction. (Typically ~ 1 vs. undulator yield of 300 γ/e-)

Where do we get MW-class laser system for ICS collisions ?

Quest for high FEL efficiency. Tapered helical undulators



- Efficiency enables higher peak power and high average power (scalability)
- FEL is a vacuum far-field interaction. Very limited losses.
- Recipe: undulator tapering + initial conditions



Nocibur: 10 um seed laser
30 % energy loss, low gain
Sudar PRL 18

FAST-GREENS 10% efficiency.
High rep-rate, high gain 515 nm

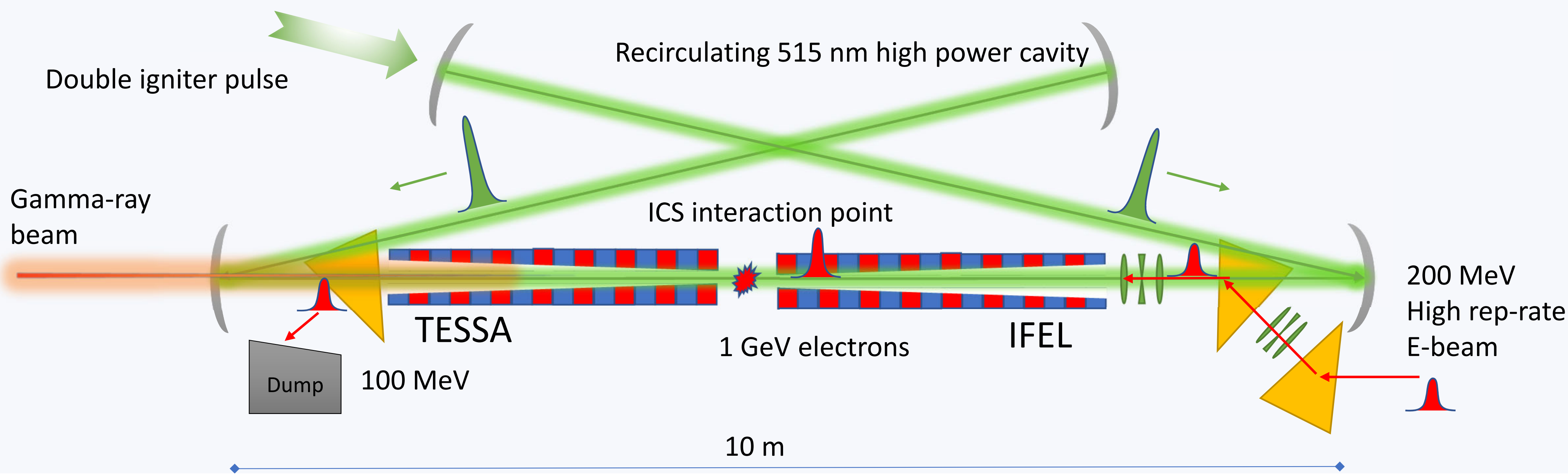
Rubicon High gradient
laser acceleration . Duris,
Nat. Comm. 2016

TESSATRON: 160 GHz 10 % efficiency high gain.
Fisher, Nat. Phot. 2022

Applications

Proposed approach: Optical energy recirculator

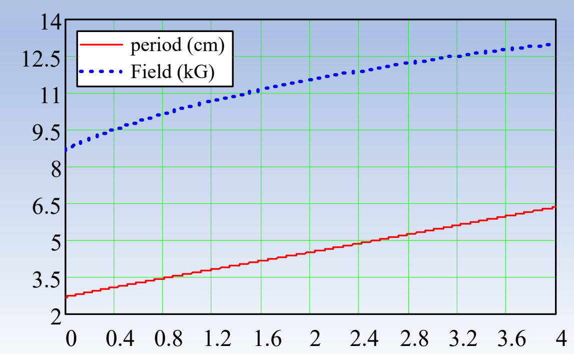
- Key observation: Due to small cross section, most of laser and e-beam energy remain in beams after ICS interaction.
- High power laser available to recirculate and accelerate electrons.
    1. Use IFEL to boost energy from SRF linac to 1 GeV
    2. ICS collisions to generate gamma-ray photons
    3. Reversing the acceleration process, laser energy is replenished + some extra to compensate for losses in cavity
- Repeat as many times as necessary (limit is optical power in the cavity)

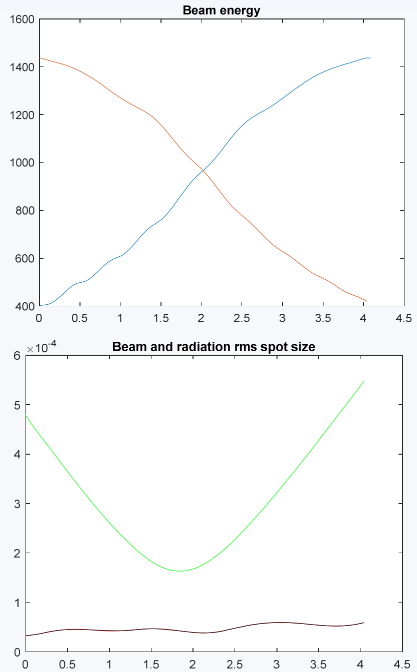


Laser-energy recovery

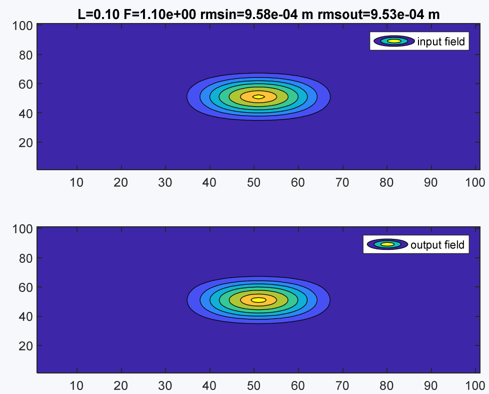
Duris, J. P., P. Musumeci, and R. K. Li. "Inverse free electron laser accelerator for advanced light sources." *Physical Review Special Topics-Accelerators and Beams* 15.6 (2012): 061301.

- Enabled on unique properties of FEL/IFEL interaction. Efficiency, large transverse acceptance, no losses.
- Assuming 4 m of tapered helical undulator with an average K = 5.0, the minimum power required to go from 200 MeV to 1 GeV is 5 TW
- 6 J - 1.2 ps bunch length. Adding 0.15 J per pass from additional TESSA deceleration
- Self-consistent 3D Genesis simulations

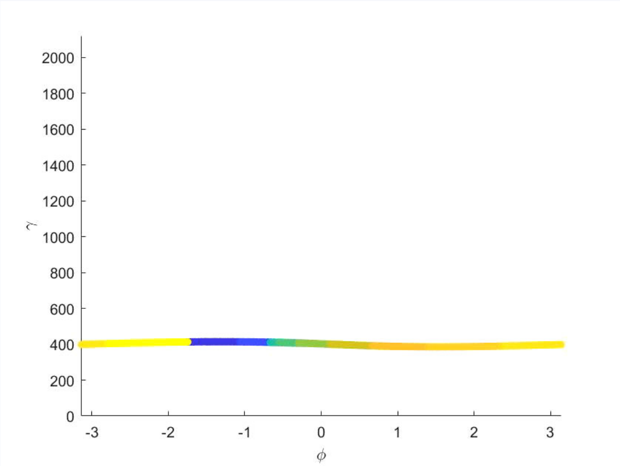




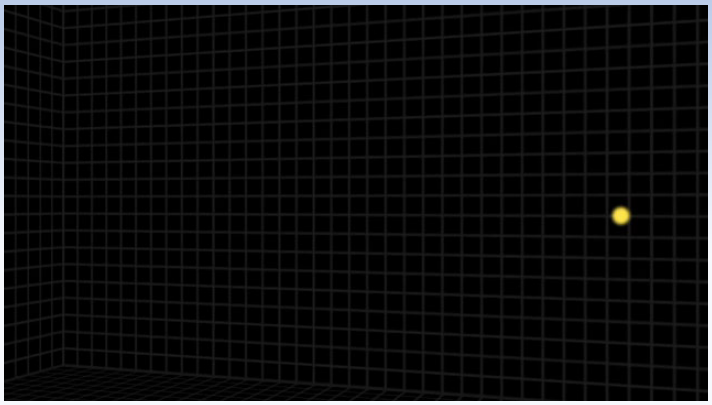
Laser profile IFEL and TESSA sections



Longitudinal phase space

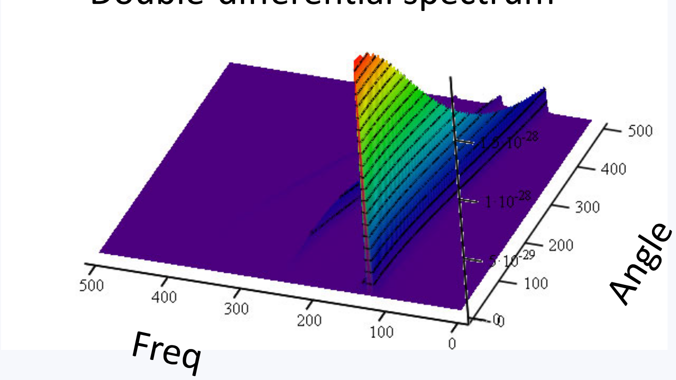


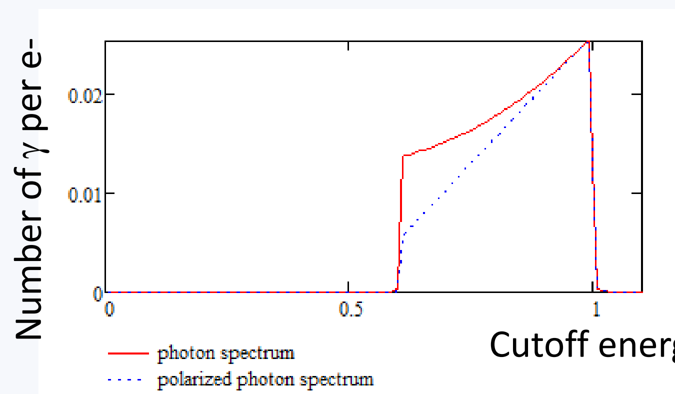
ICS interaction to generate pol. Gamma rays



Ebeam energy	1 GeV
Ebeam/laser pulse duration	1.2 ps
Ebeam charge	3.2 nC
Laser wavelength	515 nm
Laser energy	6 J
Laser spot size (1/e2)	10 um
E-beam spot size (rms)	5 um
Integrated photon yield	0.8 γ/e-

Double-differential spectrum



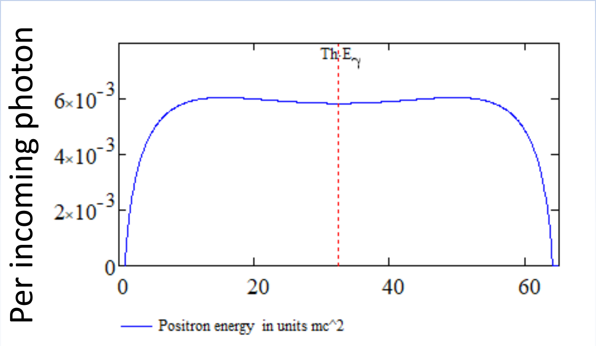


Angular cutoff 0.5 mrad

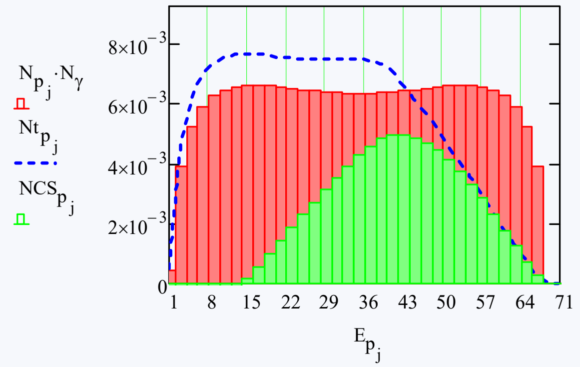
Cutoff energy for ICS: 35 MeV

Polarized positron generation

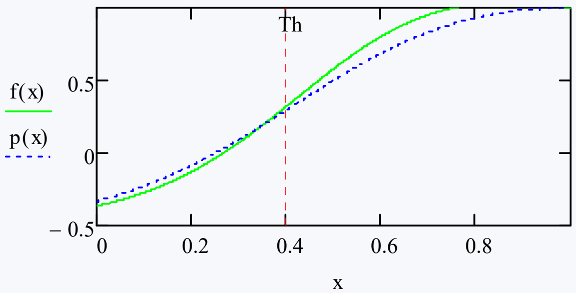
- Pair production cross-section *Motz, Olsen, Kock, RMP 41 581 (1969)*
  - Consider 0.8 rad length thick target (3 mm for tungsten)
- Polarization of positrons vs. cut-off energy
  - Michailichenko - *LC02, Proceedings, SLAC-WP-21*.
  - Olsen and Maximon - *Physical Review* 114.3 (1959): 887.



Using actual photon spectrum from ICS source



Assume a capture threshold at 14 MeV
0.1 polarized e+ per incoming e-
0.14 total e+ per e-
Polarization 0.7 (neglecting depolarization in target) !



x = 1 corresponds to 34 MeV photon energy

Polarized positron flux: some numbers

- $2 \cdot 10^{14}$ e+/s are required by ILC
- Need to start with $2 \cdot 10^{15}$ e-/s or 320 μA average current
- Can be packaged/divided in different time-format depending on damping ring and optical recirculation cavity. For the sake of discussion let us consider a 3.2 nC bunches at 100 KHz repetition rate (9 MHz bursts with 0.011 duty cycle)
- Average e-beam power of SRF linac to 200 MeV -> 65 kW
- IFEL acceleration to 1 GeV (2.5 J laser energy or 40 % of 6 J circulating laser energy in cavity).
- TESSA deceleration back to 100 MeV (give back to laser 2.9 J to compensate for cavity losses up to 6.4 % per pass)
- Laser intra-cavity average power 600 kW

Ongoing FAST-GREENS project

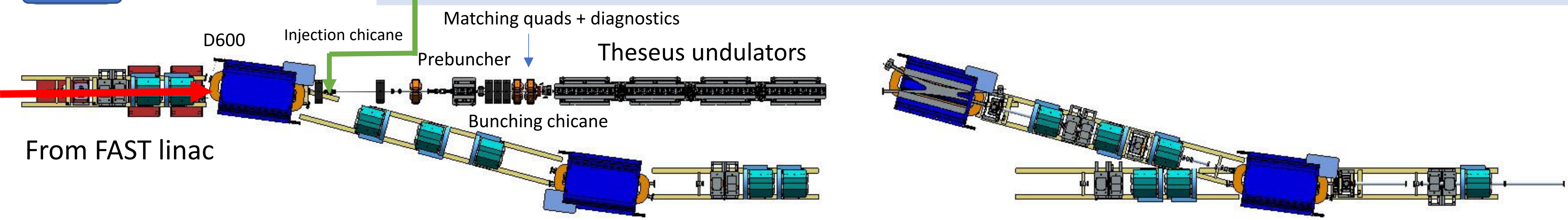
- UCLA – RadiaBeam – ANL – FNAL – collaboration
- Main scientific goals:
  - First experimental **measurements of spectral and transverse profile characteristics** of the radiation amplified in the TESSA regime of operation.
  - Demonstration of single pass **record high energy extraction efficiency** from a relativistic electron beam in the VIS region
  - Couple SRF linac with high efficiency undulator to open the path to MHz-rep rate Tapering Enhanced Oscillator multi-kW high power lasers
  - Enable high rep-rate Inverse Compton Scattering based polarized gamma-ray sources for nuclear physics/polarized positron production

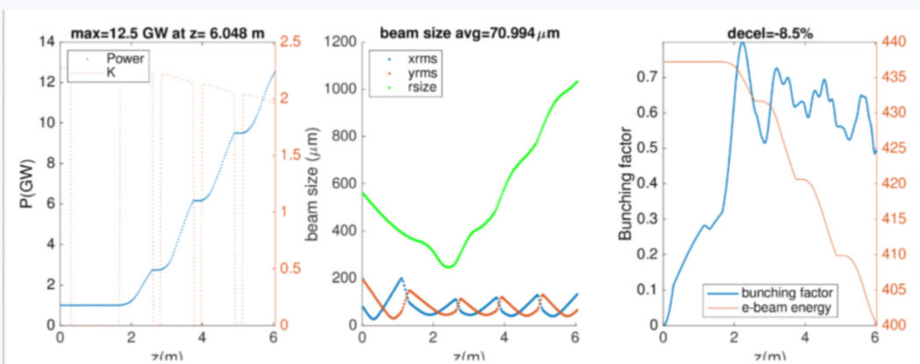
Beam Energy	**220 MeV**
Peak current	0.6 kA
Emittance	3 um
Charge	1 nC
Energy spread	0.1 %
Undulator length	4 x 0.96 m
Radiation wavelength	**515 nm**
Seed power	1 GW
Interaction geometry	Helical

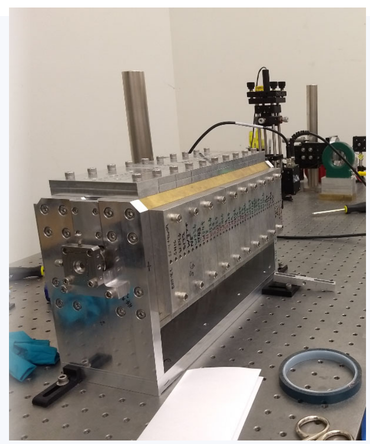
FAST-GREENS experimental status

Amplitude Magma system

- Hardware shipped to FNAL
- Start with 1 prebuncher + 2 undulator experiment
- Measurements to validate beam parameters
- Seed laser to be delivered in March 2023







ICS-based gamma-ray production

For high flux gamma ray production via Compton the main issue is the laser rate. Hiγs @ TUNL/Duke uses an FEL + storage ring to generate ~10^10 ph/sec

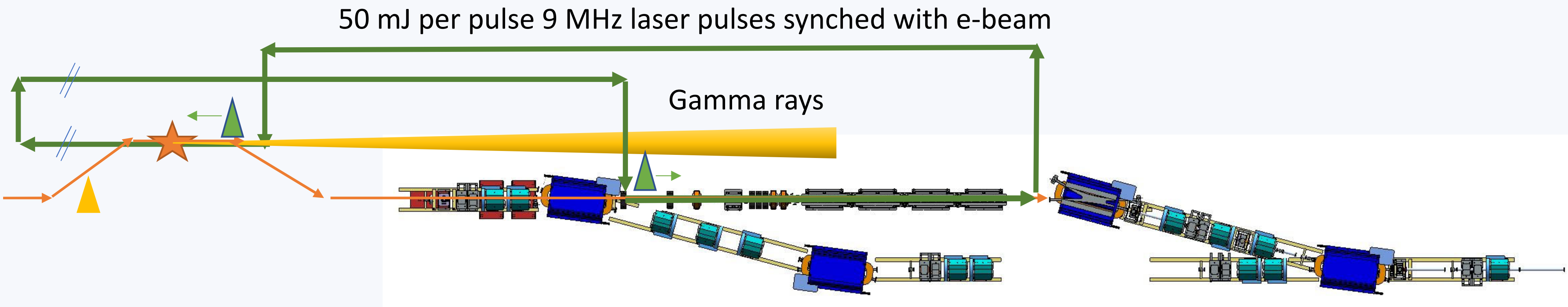
Tunability (limited by optics) scales as γ^4

@ 9 MHz train / 5 Hz -> 5·10^11 photons/sec – ps pulses

Synchronization scheme depends on implementation. A possibility is two light pulses in a 2x longer cavity

Helical geometry - > Circularly polarized gammas

Parameter	Value
E-beam energy	220 MeV
E-beam charge	1.2 nC
Laser energy	50 mJ (20% efficiency)
Laser wavelength	515 nm
Gamma ray energy	1.8 MeV
Gamma ray flux	>10^7 per shot



Conclusion and summary

- Polarized positron production open challenge for next linear collider
- ICS-based approach can benefit from high efficiency FEL technology
- FAST-GREENS program aimed at demonstrating TESSA technology at visible wavelength
  - First experiments would open up path to investigate high repetition rate TESSA, high average power cavity and gamma ray production
- Also Compton-ring + stacking laser cavity and other solutions should be considered !
- Overlap with gamma-gamma program

TESSA: FAST-GREENS collaboration

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Funding agencies : DOE SBIR/STTR program, DOE BES (SCGSR + UCLA)